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Process properties of electronic high voltage discharges triggered by ultra-short pulsed laser filaments

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Abstract

Remote processing of metallic workpieces by techniques based on electric arc discharge or laser irradiation for joining or cutting has a long tradition and is still being intensively investigated in present-day research. In applications that require high power processing, both approaches exhibit certain advantages and disadvantages that make them specific for a given task. While several hybrid approaches exist that try to combine the benefits of both techniques, none were as successful in providing a fixed electric discharge direction as discharges triggered by plasma filaments generated by ultra-short pulsed lasers. In this work we investigate spatial and temporal aspects of laser filament guided discharges and give an upper time delay between the filament creation and the electrical build-up of a dischargeable voltage for a successful filament triggered discharge.

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1. Introduction

Technologies for material processing can be basically classified into two categories: technologies that require a direct contact between the work piece and the processing tool (e.g. machining based on material removal, friction welding, resistance welding etc.) and remote technologies that allow for a gap between the work piece and the processing tool (e.g. arc welding, laser processing, electron beam joining etc. [1]). This classification is independent

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of the type of processing (e.g. joining, cutting or structuring) as well as of the material properties of the work piece (e.g. conductivity, state of matter, chemical composition etc.).

Since the advantages of remote processing lie closely at hand, the corresponding technologies are prevalent in many application areas. Nevertheless, for certain applications only few distinct processing technologies have emerged. For instance remote laser processing where the laser beam is deflected by a fast galvanometric scanner and focused by imaging optics on the workpiece offers high processing speeds and allows to process workpieces that have spatial extents. The disadvantages are mainly of system technological nature such as the effort to generate the laser of sufficient power and to guide the beam towards the work piece. Especially for laser powers in the range of several kilowatts the system technology can become quite challenging, since depending on the energy efficiency of the laser generation an active thermal cooling must be employed to dissipate a thermal power that can be up to 4 or 5 times higher than the generated laser power. Also, for laser powers in the kilowatt range galvanometric scanner mirrors have to be designed for active cooling, thus making them more massive which limits in turn the achievable acceleration of the mirrors. This leads to constraints on the maximum feed speed at which the spatial features of a given structure can be marked without penalties on the precision.

In contrast to laser remote processing various electric arc techniques are present that offer high power (due to more efficient power conversion) but have to be guided closely to the work piece’s surface. Consequently, any automation must utilize robot or portal systems and requires workpieces with rather flat surface geometries in order to prevent a deflection of the electric arc due to an inappropriate electric field gradient originating from a curved surface. Because the mechanisms for such systems are typically rather bulky, the processing speeds are again limited in spite of sufficient electric power that would allow, at least in principle, faster processing.

Of course, it is obvious to merge laser and electric arc processing to benefit from the advantages of both technologies. This research topic has received intensive consideration over the recent years where different groups investigate this so-called laser-arc hybrid welding technology [2-4]. In such case the laser helps to stabilize the electric arc discharge by additional heating of the workpiece’s surface (faster transformation from solid to gaseous) and by heating the plasma region of the discharge thus providing a higher conductivity at the laser position within the discharge. Nevertheless, a mechanical system for the positioning of the electric arc relatively close to the work piece surface is still necessary.

A big step toward remote laser arc processing has been achieved by the so-called “laser assisted arc welding“ (LAAW) developed by Albright et. al. [5,6], where inside a processing chamber with carbon monoxide atmosphere a carbon monoxide laser is used to generate plasma within the gas by linear absorption. Since the plasma is conductive an electric discharge can be guided for significant distances onto the workpiece. Nevertheless, even though some non-toxic processing gasses with specific laser wavelength combinations have been found [6], the LAAW process exhibits still some disadvantages, such as higher beam divergence due to the presence of plasma, because every plasma exhibits a refractive index below one [7,8]. As the absorption process inside the gas is linear (Beer-Lambert law), the (typically divergent) laser beam may create plasma along its whole cross-section thus making the positioning of the electric arc discharge less accurate. Furthermore, the wider plasma cross section could also provide an electric arc with a wider cross section thus making (the often desired) plasma keyhole processing of the work piece less efficient [9].

Parallel, there have been efforts to use highly energetic ultra-short laser pulses to generate several kilometers long plasma filaments for controlled discharge of atmospheric lightning [10-12] (without any intentions of material processing). In this case the plasma filament is generated by a laser pulse that experiences self-focusing due to the nonlinear optical Kerr-effect [13]. The self-focusing occurs only for pulses that have a peak power that is higher than the critical power for self-focusing [14]. For air and a laser at 800 nm the critical peak power is approximately above 3 GW. If the pulse peak power exceeds this value the self-focusing overcomes the natural beam divergence of a Gaussian beam, causing the beam to focus within a finite distance. However, during the collapse the beam size does not become indeterminately small, because if the beam diameter grows sufficiently small the intensities grow high enough ionize air by nonlinear absorption processes [15] thus creating a plasma. As already pointed out, the plasma causes a divergence of the laser beam. This leads in combination with the ongoing self-focusing to a dynamic equilibrium between self-focusing and plasma-caused defocusing. The maximum achievable intensity inside a single filament is limited (intensity clamping) [16] causing a single laser beam to split up into several parallel propagating filaments if the pulse peak power is high enough. The length of the plasma filament is pulse energy dependent

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